Annual Progress Report

III-V HETEROJUNCTION STRUCTURES AND HIGH SPEED DEVICES

U.S. Air Force AFOSR 86-0111

February 29, 1988

Principal Investigator

H. Morkoc

University of Illinois at Urbana-Champaign

Coordinated Science Laboratory

1101 W. Springfield Avenue

Urbana, Illinois 61801

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

AD-A195 464

REPORT DOCUMENTATION PAGE

DTIC ELECTE MAY 2 0 1988 S D

1a. REPORT SECURITY CLASSIFICATION	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release, distribution unlimited
2b. DECLASSIFICATION / DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S)	5. MONITORING ORGANIZATION REPORT NUMBER(S) AFOSR-TR- 88-0530
6a. NAME OF PERFORMING ORGANIZATION University of Illinois Coordinated Science Lab 6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION AFOSR/NE
6c. ADDRESS (City, State, and ZIP Code) 1101 W. Springfield Ave. Urbana, IL 61801	7b. ADDRESS (City, State, and ZIP Code) AFOSR/NE Bolling AFB, DC 20332-6448
8a. NAME OF FUNDING/SPONSORING ORGANIZATION AFOSR 8b. OFFICE SYMBOL (If applicable) NE	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER AFOSR-86-0111
8c. ADDRESS (City, State, and ZIP Code) AFOSR/NE Bolling AFB, DC 20332-6448	10. SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO. 61102F PROJECT NO. 2305 TASK NO. C1 WORK UNIT ACCESSION NO.

11. TITLE (Include Security Classification)

III-V Heterojunction Structures & High Speed Devices

12. PERSONAL AUTHOR(S)

Professor Hadis Morkoc

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Annual	FROM 1 Feb 87 TO 31 Jan 88	March 8, 1988	37

16. SUPPLEMENTARY NOTATION

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

A systematic investigation of the $In_yGa_{1-y}As/Al_{0.15}Ga_{0.85}As$ pseudomorphic MODFET has revealed an optimum InAs mole fraction of $0.15 \leq y \leq 0.20$. Meanwhile, continuing studies of the InGaAs/GaAs strained layer MQW by optical transmission and photoreflectance have displayed sharp spectral features, revealing the excellent optical quality of the samples. With good agreement between the measured spectra and our band structure model, an increased understanding of the InGaAs/GaAs strained layer heterojunction has been achieved. Fabricating InGaAs/GaAs MQW structures into p-i-n optical modulators, large 27% changes in transmission have been reported. Operating this MQW electroabsorption optical modulator as a Self-Electroopic Effect Device, we have reported the first demonstration of this device in the InGaAs material system.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT ☐ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION Unclassified
22a. NAME OF RESPONSIBLE INDIVIDUAL Dr Jerry Witt	22b. TELEPHONE (Include Area Code) (202) 767-4932 22c. OFFICE SYMBOL NE

DD FORM 1473, 84 MAR 83 APR edition may be used until exhausted. All other editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE

UNCLASSIFIED

University of Illinois
at Urbana-Champaign

Coordinated Science Laboratory
1101 West Springfield Avenue
Urbana, IL 61801-3082
USA

(217) 333-0722

College of Engineering

AFOSR-TR- 88-0530

March 8, 1988

Capt. Gregory Rosalia
AFOSR-PKD
Bldg. 410
Bolling Airforce Base
Washington, DC 20332-6448

Dear Capt. Rosalia:

Please find enclosed a copy of our Annual Progress Report for Grant No. AFOSR-86-0111. A copy of the report has also been sent to the program manager, Dr. Gerald Witt.

Sincerely,

James J. Chen for Hadis Morkoç

Hadis Morkoç

Enclosure

HM:jjc

DTIC
COPY
INSPECTED
1

Accesion For	
NTIS CRA&I	✓
DTIC TAB	☐
Unannounced	☐
Justification	
By	
Distribution /	
Availability Codes	
Dist	Avail and/or Special
A-1	

NE | Dr. Witt
please
review

TABLE OF CONTENTS

III-V HETEROJUNCTION STRUCTURES AND HIGH SPEED DEVICES

I. Summary

Dramatic reductions have been achieved in alloyed and non-alloyed contact resistance to n-type InGaAs through the use of an InAs cap layer. We report best ever specific contact resistances of 2.6×10^{-8} Ω*cm^2 and less than 1.7×10^{-8} Ω*cm^2 for non-alloyed and alloyed contacts, respectively. Application of this contacting technique to the source and drain of FET structures and to the emitter and perhaps base of HBT and HET structures is expected to produce improvements in device performance and reproducibility.

Results on the use of an InAs cap layer on an InGaAs/InAlAs double HBT have already been reported. For a 50 μm x 50 μm active device area, we reported a highest ever common emitter current gain of 1500 at collector current densities of 2.7×10^3 A/cm^3, with an offset voltage of less than 50 mV.

A systematic investigation of the $In_yGa_{1-y}As/Al_{0.15}Ga_{0.85}As$ pseudomorphic MODFET has revealed an optimum InAs mole fraction of $0.15 \lesssim y \lesssim 0.20$. Meanwhile, continuing studies of the InGaAs/GaAs strained layer MQW by optical transmission and photoreflectance have displayed sharp spectral features, revealing the excellent optical quality of the samples. With good agreement between the measured spectra and our band structure model, an increased understanding of the InGaAs/GaAs strained layer heterojunction has been achieved. Fabricating InGaAs/GaAs MQW structures into p-i-n optical modulators, large 27% changes in transmission have been reported. Operating this MQW electroabsorption optical modulator as a Self- Electrooptic Effect Device, we have reported the first demonstration of this device in the InGaAs material system.

Growth of InGaAs/GaAs superlattices, as well as GaAs/AlGaAs superlattices, on Si substrates has also been performed with sharp spectral features again revealing the good quality of the epilayers. Meanwhile, investigation of thermal annealing of the GaAs/Si heterointerface has

proceeded. Significantly, the electrical characteristics of the annealed p-GaAs/n-Si heterojunction is observed to approach those of in-situ grown p/n homojunctions. Extrapolated C-V intercept voltages uniformly approach their predicted 1.17 V value. Ideality factors all improved with annealing with values as low as 1.5, while leakage currents were reduced by three orders of magnitude. These junction characteristics are acceptable for device applications. An integrated GaAs/Si HBT has therefore been proposed with potentially superior high speed performance, and proper transistor action in such a device has been observed.

An InGaAs/InAlAs HET with a 600 Å thick base has displayed best hot electron transfer ratios and differential hot electron transfer ratios of 0.91 and 0.98, respectively. Meanwhile, a peak ballistic transfer ratio of 0.82 was reported in this structure, along with the observation of a transmission resonance above the collector barrier.

II. Progress Made

Low Resistance Contacts

Using an InAs contact layer, we have reported extremely low alloyed and non-alloyed n-type ohmic contact resistances on $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ structures grown on InP. Using an extended Transmission Line Model, specific contact resistances of $2.6 \times 10^{-8}\ \Omega \cdot cm^2$ and $2.9 \times 10^{-11}\ \Omega \cdot cm^2$, with corresponding transfer resistances of 0.018 Ω*mm and 0.0006 Ω*mm, were measured for the non-alloyed and alloyed contacts, respectively. Given the standard error in the measured resistances, however, we reported an alloyed specific contact resistance of only $1.7 \times 10^{-8}\ \Omega \cdot cm^2$. Nevertheless, these ohmic contact resistances are by far the best values ever achieved in this material system to date. Investigation of p-type ohmic contacts using the InAs cap layer are currently under way. Additionally, use of a strained InAs cap layer on GaAs/AlGaAs structures is also under investigation.

Field Effect Transistors

With the uniformity and observed reproducibility of the low resistance non-alloyed contacts, specific device applications for this InAs cap layer are clearly envisioned. One application of this contacting technique is in the formation of low resistance contacts ot the source and drain of FET device structures. Preliminary results on an InGaAs/InAlAs MODFET reveal transfer resistances of the source and drain contacts of less than 0.08 Ω*mm. For the devices investigated to date, highly uniform room temperature transconductances of around 250 mS/mm have been measured repeatedly for 1 μm gate lengths. Using optimized processing, further reductions in contact resistance are expected, which should result directly in improved transconductances.

Doped channel InGaAs MISFETs with an InAs cap layer have also been investigated. These doped channel structures offer potentially larger current capabilities and transconductances because of their higher channel carrier densities, with reductions in carrier mobilities not expected to dramatically reduce performance in submicron gate-length devices. With low transfer resistances of less than 0.08 Ω*mm, devices with 1 μm gate lengths exhibited transconductances of 125 mS/mm at 300 K and 275 mS/mm at 77 K, while displaying excellent pinch-off and saturation characteristics. These preliminary results should improve significantly with optimization of the device structure. Meanwhile, increased current driving capability is also being investigated through the use of multiple channels in a pseudomorphic MODFET. Devices with two and three channels have demonstrated increased currents while maintaining excellent cut- off characteristics.

Finally, work has continued on the study of $In_yGa_{1-y}As/GaAs$ strained layer multiple quantum wells (MQWs) to better understand the characteristics of the InGaAs/GaAs heterojunction. These studies have been pursued in efforts to achieve better psuedomorphic MODFET device performance. Using low temperature optical transmission and room temperature photoreflectance, sharp transistions were observed in the measured spectra revealing the excellent optical quality of the samples, with excitonic transitions up to 3C-3H (3rd conduction and 3rd valence heavy-hole subbands). Using Kane's three band model (including strain effects), calculation of the band structure was performed showing good agreement with measurement. By fitting the experimental results, a heavy-hole valance band discontinuity of 30% was obtained for $0.13 \leqslant y \leqslant 0.193$.

Applying our understanding of the InGaAs/GaAs strained layer heterojunction, $In_yGa_{1-y}As/Al_{0.15}Ga_{0.85}As$ pseudomorphic MODFETs were systematically investigated to determine the optimum InAs mole fraction and InGaAs well thickness. From detailed characterization by transmission electron microscopy (dislocation images), Hall measurement (mobilities and sheet carrier concentrations), and photoreflectance (energy subband transitions), we reported a peak in device performance for InAs mole fractions $0.15 \lesssim y \lesssim 0.20$: for a 1 μm gate device with a 150 Å $In_{0.20}Ga_{0.80}As$ quantum well, an extrinsic transconductance of 310 mS/mm was reported at room temperature.

Multiple Quantum Well Optical Modulators

Transmission measurements on undoped as well as heavily modulation doped GaAs/AlGaAs multiple quantum wells (MQWs) have been extensively studied to examine the mechanisms that influence the excitonic absorption lineshape. Optical modulators based upon the strong field dependence of optical absorption (electroabsorption) have previously been demonstrated. Namely, using the quantum confined Stark effect, AlGaAs/GaAs MQW p-i-n modulators were demonstrated. Through our continuing studies of InGaAs/GaAs strained layer MQWs, we have extended our research towards the investigation of an InGaAs/GaAs MQW optical modulator. Operating in the far infrared, the InGaAs material is of considerable interest because of its compatability with optical communication systems. Using photocurrent and transmission measurements, large excitonic absorption resonances were observed at room temperature in the InGaAs/GaAs MQW structure. Fabricated into p-i-n optical modulators, changes in the transmission of 27%, corresponding to a change in the abosorption coefficient of 2260 cm^{-1}, were recorded for an applied reverse bias of 6 V, at a wavelength of 0.975 μm. Operating this MQW electroabsorption optical modulator as a Self-Electrooptic Effect Device, the first demonstration of clear non-linear optical input-output characteristics was reported for this important material system. Investigation of an InGaAs/GaAs MQW optical modulator on a Si substrate are currently under way. The realization of this structure will offer exciting possibilities in combining optical communication systems with Si circuits.

GaAs on Si

In our on-going research into growing III-V semiconductors on Si substrates, the growth of GaAs/AlGaAs and InGaAs/GaAs superlattices on Si substrates was investigated using photoreflectance studies to determine the quality of the epilayers. We have reported sharp spectral features from various subband tranisitions indicating good quality of the epilayer using suitable growth techniques.

The investigation of thermal annealing on the properties of the GaAs/Si heterojunction has proceeded in collaboration with N. Otsuka of Purdue University, P. Gourley of Sandia National

Laboratories, and P. Raccah of the University of Illinois at Chicago. Plan-view TEM has revealed dislocation densities of the annealed samples in the low $10^5\ cm^{-2}$ range, a three to four orders of magnitude reduction from the as-grown samples. As expected, threading dislocations are dramatically reduced with annealing, while a network of misfit dislocations is enhanced. Notably, the $\approx$100 Å spacing between the misfit dislocations agree well with the theoretical spacing of mismatch accommodation by only Type I dislocations (99 Å). Using a larger field scanning photoluminescence technique, defect densities of samples annealed at 850 °C were measured to be $1x10^6\ cm^{-2}$ and $6x10^6\ cm^{-2}$ for shallow and deep excitation, respectively. Finally, preliminary electroreflectance studies have been performed suggesting a compressive strain of the GaAs localized within $\approx$600 Å of the heterointerface.

Applying the results on the quality of the GaAs on Si to refined growth and processing, the electrical characteristics of the heterointerface was investigated in a p-GaAs epilayer on n-Si substrate diode. As previously reported, capacitance-voltage measurements performed on as-grown GaAs on Si samples displayed extrapolated intercept voltage values varying from 1.5 to 2.5 V between Si wafers. After annealing for 20 min at 850 °C, the intercept voltages were found to approach their predicted value of 1.17 V with the variation in intercept voltages between Si wafers dramatically reduced. The effects of annealing were also observed in the enhancement of current-voltage characteristics. Ideality factors as low as 1.5 were measured for the annealed p-GaAs/n-Si diode, as compared to values greater than 2 measured for the as-grown diodes. Similar improvements were also exhibited in the reverse bias properties with a three orders of magnitude reduction in leakage current achieved as a consequence of annealing. These results show that possible interface reconstruction between Si and GaAs reduce, if not eliminate, the postulated large electric field at the GaAs/Si(100) interface.

Achievement of excellent junction properties between Si and GaAs suggest the integration of GaAs and Si within the same device. Pursuing the realization of such a novel device, a study was undertaken to examine the potential performance of a n-AlGaAs emitter, p-GaAs base on a n-Si collector heterojunction bipolar transistor (HBT). Such a device structure combines the high frequency capability of the GaAs/AlGaAs system with the advanced processing technology of Si. Detailing a possible implementation of a GaAs/Si HBT, dramatic reductions in device parasitics are anticipated from its self-aligned structure. Using a compact transistor model, calculations of the high speed capability of the transistor were performed revealing performance values superior to those predicted for realizable GaAs/AlGaAs HBTs with equivalent design parameters. Specifically, optimized f_{max} = 110 GHz and $f_{max} = f_t$ = 94 GHz were predicted for the GaAs/Si HBT as compared to 108 GHz and 76 GHz, respectively, for a comparable GaAs/AlGaAs HBT. As these simulations made use of fairly conservative dimensions and device parameters, the simulated results are encouraging and suggest further investigation of this device. Efforts to realize the GaAs/Si HBT are currently under way. Investigating relatively large dimension transistor structures, preliminary results on the GaAs/Si HBT show proper transistor action.

Heterojunction Bipolar Transistors

In our study of the heterojunction bipolar transistor (HBT), analysis of an $In_{0.53}Ga_{0.47}As/InP$ double HBT (DHBT) was performed to determine the relative merits of this material system. Using a compact transistor model, optimized current gain cutoff frequencies in excess of 150 GHz and a maximum oscillation frequency of 138 GHz are theoretically predicted for an $InP/In_{0.53}Ga_{0.47}As$ transistor.

Meanwhile, in conjunction with our simulations of device performance, an $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ double heterojunction bipolar transistor (DHBT) was investigated using the InAs contacting technique. This high current handling device is of significant practical importance in driving lasers in opto-electronic integrated circuits. With specific contact resistances of less than $1.5 \times 10^{-7}\ \Omega{*}cm^2$ for non-alloyed n-type contacts, maximum common emitter current gains of 1500 are reported at collector current densities of 2.7×10^3 A/cm^3. To our knowledge, this is the highest current gain reported for this HBT structure prepared by MBE. Note that the common emitter output characteristics of this reported structure exhibited an offset voltage of less than

50 mV. Further optimization of the device structure is currently proceeding. Additionally, investigation of a p-n-p InGaAs/InAlAs DHBT is also under way. Finally, we hope to eventually perform microwave measurements on these transistors, which currently await a new microwave test fixture.

Hot Electron Transistors

Work has continued in the exploration of $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ hot electron transistors (HET). While the HET is typically operated at low temperature to reduce the background thermal current and thereby enhance the injected current, the large conduction band discontinuity between $In_{0.53}Ga_{0.47}As$ and $In_{0.52}Al_{0.48}As$ permits operation of the InGaAs/InAlAs HET at elevated temperatures. With a reduced thickness of the base transit region (600 Å), collection of nonthermal electrons was observed at 300 K. A differential transfer ratio α=0.35 was measured at the hot electron peak at room temperature. At 77 K, an impressive α=0.98 hot electron transfer ratio was measured with a corresponding dc transfer ratio of 0.91. These hot electron gains are superior to those previously reported for GaAs/AlGaAs and InGaAs/InAlAs HETs with even thinner base layers.

Meanwhile, investigation of ballistic transport through the 600 Å thick base of the HET was further pursued. We have reported a 77 K peak ballistic transfer ratio of 0.82. The appearance of a secondary conductance peak near V_{CB}=0 in these results is attributed to a transmission resonance in the energy continuum above the collector barrier. Due to thermal smearing effects at 77 K, resolution of the multiple energy peaks from the resonant (virtual) states was not resolved; rather, a single diffuse resonant enhanced peak was observed. Further improvements in the performance of our hot electron transistors is currently limited by our ability to achieve reproducible, low resistance ohmic contacts to the thin base (and emitter) layer. Use of the InAs cap layer for extremely low non-alloyed ohmic contacts should greatly improve measured ballistic tranport characteristics, with potentially useful device gains.

A more detailed presentation of our results are given in the abstracts of some representative papers, included in the following pages. For those desiring to review the complete papers, we have provided cross referencing of the attached abstracts with the list of latest publications. This attached list of publications includes essentially all the journal articles and conference abstracts printed and/or submitted in 1987, including AFOSR supported research as well as research supported by other grants.

III. Representative Papers

EXTREMELY LOW NON-ALLOYED AND ALLOYED CONTACT RESISTANCE USING AN InAs CAP LAYER ON InGaAs BY MOLECULAR BEAM EPITAXY

by

C. K. Peng, J. Chen, J. Chyi, and H. Morkoç

University of Illinois at Urbana-Champaign

Coordinated Science Laboratory

1101 W. Springfield Avenue

Urbana, IL 61801

ABSTRACT

Extremely low alloyed and non-alloyed ohmic contact resistances have been formed on n-type $InAs/In_{0.53}Ga_{0.47}As$ /$In_{0.52}Al_{0.48}As$ structures grown on InP(Fe) by molecular beam epitaxy. To insure the accuracy of the small contact resistances measured, an extended Transmission Line Model was used to extrapolate contact resistances from test patterns with multiple gap spacings varying from 1 μm to 20 μm. For a 150 Å thick InAs layer doped to 2 x 10^{18} cm^{-3} and a 0.1 μm thick InGaAs layer doped to 1 x 10^{18} cm^{-3}, a specific contact resistance of 2.6 x 10^{-8} Ω*cm^2 was measured for the non-alloyed contact, while a resistance less than 1.7 x 10^{-8} Ω*cm^2 is reported for the alloyed contact. Conventional Au-Ge/Ni/Au was used for the ohmic metal contact and alloying was performed at 500 °C for 50 seconds in flowing H_2. Using a thermionic field emission model, the barrier height at the InAs/InGaAs interface was calculated to be 20 meV.

Reference #424

DETERMINATION OF BAND OFFSETS IN AlGaAs/GaAs AND InGaAs/GaAs MULTIPLE QUANTUM WELLS.

G. Ji, D. Huang, U.K. Reddy, H. Unlu, T.S. Henderson and H. Morkoc

Coordinated Science Laboratory
University of Illinois at Urbana
1101 W. Springfield Ave.
Urbana, IL 61801

ABSTRACT

The determination of valence band offsets Q_v by fitting the optical transmission spectra for $Al_xGa_{1-x}As$/GaAs and $In_yGa_{1-y}As$/GaAs multiple quantum wells (MQWs) is discussed. The valence band offset Q_v is defined as $Q_v = \Delta E_v/(\Delta E_v + \Delta E_c)$, where ΔE_v and ΔE_c are the valence and conduction band discontinuities at the heterojunction. For $Al_xGa_{1-x}As$/GaAs (Type I for both heavy holes and light holes, i.e. electrons, heavy holes and light holes are located in the same layers) the energy separation ΔE between the first light and heavy hole subbands in the valence band is used to determine the valence band offset Q_v. In order to improve the precision, MQWs with narrow well widths and higher Al mole fraction 'x' should be used. Further, the inclusion of coupling between the valence and conduction subbands in Kane's three-band model is also essential. However, Q_v is still not determined uniquely by the above energy difference ΔE. Different combinations of Q_v and heavy hole effective masses m_{hh} in GaAs can lead to the same ΔE. The forbidden transition E_{13h} in a narrow well can be used to identify the actual values of m_{hh} and Q_v. (The designation $E_{nmh(l)}$ refers to the energy separation of the n-th conduction subband and m-th heavy (light) hole subband.) Following such a procedure, we find that $Q_v = 0.33$ and $m_{hh} = 0.34m_0$ for $Al_xGa_{1-x}As$/GaAs MQWs ($x < 0.37$).

For $In_yGa_{1-y}As$ MQWs (Type I for heavy holes and Type II for light holes, i.e. both electrons and heavy holes are located in the same layers, but the light holes are in different layers), the transition energies between the conduction subbands and the light hole valence subbands are much better parameters to determine the band offsets in comparison with the transitions involving the heavy holes. Both the optical measurements and the calculations including the strain effect show that E_{11l} between the first conduction subband and the first light hole valence subband in the

Reference #374

Optical Investigation of Highly Strained InGaAs-GaAs Multiple Quantum Wells

G. Ji, D. Huang, U.K. Reddy, T.S. Henderson, R. Houdré and H. Morkoc

University of Illinois at Urbana-Champaign

Coordinated Science Laboratory

1101 W. Springfield Ave.

Urbana, Illinois 61801

Abstract

Low temperature optical transmission spectra of several $In_xGa_{1-x}As/GaAs$ strained multiple quantum wells (MQWs) with different well widths and In mole fractions have been measured. The excitonic transitions up to 3C-3H are observed. The notation nc - mH (L) is used to indicate the transitions related to the n-th conduction and m-th valence heavy (light) hole subbands. Step-like structures corresponding to band-to-band transitions are also observed, which are identified as 1C-1L transitions. The calculated transition energies, taking into account both the strain and the quantum well effects, are in good agreement with the measured values. In these calculations the lattice mismatch between the GaAs buffer and the InGaAs/GaAs MQW is taken into account and the valence band offset Q_v is chosen as an adjustable parameter. By fitting the experimental results to our calculations, we conclude that the light holes are in the GaAs barrier region (Type II MQW) and the valence band offset Q_v is determined to be 0.30. A possible system in which the transition from Type I to Type II for light holes might be observed is also discussed.

Reference #375

Interband Transitions in $In_xGa_{1-x}As/GaAs$ Strained Layer Superlattices

U.K. Reddy, G. Ji, T. Henderson, D. Huang, R. Houdré and H. Morkoc

University of Illinois at Urbana-Champaign
Coordinated Science Laboratory
1101 W. Springfield Ave.
Urbana, Illinois 61801

Cole W. Litton

AFWAL/AADR, Bldg. 620
Avionics Laboratory
Wright-Patterson AFB, Ohio 45433

Room temperature photoreflectance (PR) measurements have been used to investigate the optical transition energies in $In_xGa_{1-x}As$/ GaAs Strained layer superlattice structures grown by molecular beam epitaxy (MBE). Sharp PR features indicating excellent optical quality of these MBE grown structures were observed. The transition energies were calculated and PR spectra fitted to the theoretical lineshape expression. By observing the variation of C1-Lb1 (where C1 is the first conduction subband in InGaAs layers and Lb1 is the first light-hole subband in the GaAs layers) Type II superlattice transition, which cannot be observed with photoluminescence even at low temperatures, a conduction band discontinuity of 70% was obtained. Further, an important outcome of this study is the observation of strong PR features from the spatially indirect C1-Lb1 transition which indicates that the modulation of band-to-band transitions can be a dominant PR lineshape determining mechanism.

PACS numbers 78.65-S, 78-65-Fa

Reference #384

Characterization of Pseudomorphic InGaAs/AlGaAs MODFET Structures Grown by Molecular Beam Epitaxy

T. Henderson, U.K. Reddy, G. Ji, H. Morkoç,
Coordinated Science Laboratory
University of Illinois at Urbana-Champaign
1101 W. Springfield Ave., Urbana IL 61801 USA (217) 333-8308

N. Otsuka
Department of Materials Science, Purdue University
West Lafayette, IN 47907

InGaAs/AlGaAs pseudomorphic MODFETs have been the focus of a great deal of attention lately because of their superior DC and microwave performance. Because of the enormous potential of these devices, important parameters, such as InGaAs layer thickness and mole fraction must be optimized.

Pseudomorphic MODFET structures were grown by MBE on undoped GaAs substrates. A typical structure had a 1um unintentionally doped GaAs buffer, followed by an $In_yGa_{1-y}As$ quantum well of thickness between 35A(y=.30) and 200Å(y=.15 or less), a 30Å undoped $Al_{.15}Ga_{.85}As$ spacer region, 350Å of $Al_{.15}Ga_{.85}As$ doped $n=3x10^{18}/cm^3$, and a 200Å GaAs cap also doped $n=3x10^{18}/cm^3$. Layers with In mole fractions above 0.20 also had 0.1um $Al_{.15}Ga_{.85}As$ layers 100Å before the quantum well to better confine the quantum states in the well.

One micron gate devices were fabricated using standard photolithographic techniques. DC measurements at 300 and 77K show that performance seems to peak around a mole fration of .15-.20, with 300K intrinsic transconductances of 330mS/mm and 370mS/mm for .15 and .20, respectively; both had threshold voltages around -.30V and peak current densities around 280 mA/mm. However, layers with higher mole fractions, 0.25 or more, must have InGaAs layers 100Å or thinner to prevent the formation of dislocations. Device performance degrades with increasing mole fractions above 0.20; for example, for a sample with an In mole fraction of 0.30 (35Å thick because of the high mole fraction), an intrinsic transconductance of only 230mS/mm was obtained at 300K, with a threshold voltage of -.60V and a peak current density of 230mA/mm.

Hall measurements and optical measurements confirm the device results. Measurements on the sample with a mole fraction of 0.30 (and others with mole fractions greater than or equal to 0.25) may indicate increased surface roughness scattering, alloy scattering, and conduction in the AlGaAs (higher energy levels have wave functions that spill into the AlGaAs more), leading to a 77K mobility of $3,700cm^2/V$-sec, and a sheet carrier concentration of $2.6x10^{12}/cm^2$, a very low value for electron mobility in a pseudomorphic MODFET, even taking into account the high measured carrier concentration. Photoreflectance measurements confirm these results; this layer had only one photoreflectance transition below the GaAs bandgap energy (at 1.380eV, tentatively identified as a ground state conduction subband to heavy hole transition), whereas a pseudomorphic MODFET with a 200Å $In_{.15}Ga_{.85}As$ quantum well had four transitions below this energy (at 1.252eV, 1.266eV, 1.291eV, and 1.342eV, tentatively identified as first conduction subband to first and second heavy hole subbands, second conduction subband to second heavy hole subband, and third conduction subband to third heavy hole subband transitions). Clearly, thin quantum wells, necessary with mole fractions in the .25-.30 range, result in higher subband energies, as energies have a dependence on well thickness as well as well depth; further, doubling the In mole fraction from .15 to .30 necessitates decreasing the well thickness by more than a factor of two. This yields lower 2DEG concentrations and degraded device performance. The presentation will detail the effects of InGaAs layer thickness and mole fraction, with an emphasis on optimizing device performance.

Reference #416

Excitonic Absorption in Modulation Doped GaAs/AlGaAs Quantum Wells

D. Huang, H.Y. Chu,* Y.C. Chang,* R. Houdré and H. Morkoc

Coordinated Science Laboratory
University of Illinois at Urbana-Champaign
1101 W. Springfield Ave.
Urbana, Illinois 61801

Abstract

We have performed transmission measurements in a range of undoped through heavily modulation doped GaAs/AlGaAs multiple quantum well structures (MQWS). The observed absorption spectra demonstrate quenching of the excitonic oscillations with increasing quasi-two-dimensional electron gas. The electron density corresponding to the total bleaching of the lowest excitonic oscillation is greater than or equal to $3 \times 10^{11} cm^{-2}$ for a quantum well size of 200Å Theoretical calculations of the absorption spectra which include the effect of carrier screening have been made. From the observation that the linewidth increases with the electron density, we demonstrate that the exciton lifetime reduces due to the interaction between the electrons and the excitons.

* Materials Research Laboratory, 104 S. Goodwin, Urbana, Illinois, 61801
pacs # 78.65.-s, 73.40.Lq

Reference #405

InGaAs/GaAs STRAINED LAYER MQW ELECTROABSORPTION OPTICAL MODULATOR AND SELF-ELECTROOPTIC EFFECT DEVICE

Abstract. We observed a clear excitonic absorption effect at room temperature in MBE-grown $In_xGa_{1-x}As/GaAs$ strained layer Multiple Quantum Well structures and fabricated optical p-i-n modulators on the same structures. A change of 27% in the transmission , corresponding to a change in the absorption coefficient of 2260 cm^{-1}, with 6 volt reverse bias voltage and at 9710 Å wavelength was measured. We also operated the modulator as a Self-Electrooptic Effect Device, resulting in a non-linear optical input-output characteristic.

W. Dobbelaere December 11 1987

S. Kalem

D. Huang

M. S. Ünlü

H. Morkoç

University of Illinois at Urbana-Champaign

Coordinated Science Laboratory

1101 W. Springfield Avenue

Urbana,IL 61801

Reference #430

Optical Transitions Involving Unconfined Energy States in InGaAs/GaAs Multiple Quantum Wells

G. Ji, W. Dobbelaere, D. Huang and H. Morkoc
University of Illinois at Urbana-Champaign
Coordinated Science Laboratory
1101 W. Springfield Ave.
Urbana, IL 61801

Optical transitions between the unconfined electron and confined hole states in highly strained $In_xGa_{1-x}As/GaAs$ multiple quantum wells (MQWs) have been observed in photoreflectance (PR) spectra. In some samples as many as seven structures above the GaAs barrier signal were present. We identify them as unconfined transitions between the unconfined electron states and the confined heavy hole states. At energies lower than that associated with the GaAs signal, intense transitions corresponding to such unconfined transitions were also observed, which cannot be explained by transitions between confined states. The intensities of the unconfined transitions decrease with increasing well widths, but are weakly dependent of the mole fraction x. The transmission coefficients are calculated in order to locate the positions of the unconfined subband energies. Good agreement is obtained between the experimental data and the theoretical calculation.

PACS numbers 78-65-5, 78-65-Fa

Reference #431

Investigation of GaAs/(Al,Ga)As Multiple Quantum Wells Grown on Ge and Si Substrates by Molecular Beam Epitaxy

U.K. Reddy, R. Houdré, G. Munns, G. Ji, and H. Morkoc

University of Illinois at Urbana-Champaign

Coordinated Science Laboratory

1101 W. Springfield Avenue

Urbana, Illinois 61801

M. Longerbone and L. Davis

Perkin Elmer MBE

6509 Flying Cloud Drive

Eden Prairie, MN 55344

B.P. Gu and N. Otsuka

School of Materials Engineering

Purdue University

West Lafayette, Indiana 47907

ABSTRACT

We report the first pl..toreflectance studies on GaAs/(Al,Ga)As multiple quantum wells grown on Si and Ge substrates. The sharp spectral features observed from various subband transitions indicate that good epilayer quality can be obtained on non-polar substrates using suitable growth techniques. The experimental results agree well with calculated values based on the envelope function approximation, when the effect of residual strain resulting from the large difference in thermal expansion between GaAs and Si is taken into account.

Reference #345

Investigation of GaAs/$Al_xGa_{1-x}As$ and $In_yGa_{1-y}As$/GaAs Superlattices on Si Substrates

U.K. Reddy, G. Ji, D. Huang, G. Munns, and H. Morkoç

University of Illinois at Urbana-Champaign

Coordinated Science Laboratory

1101 W. Springfield Avenue

Urbana, IL 61801

Abstract

We have studied for the first time the optical properties of GaAs/$Al_xGa_{1-x}As$ lattice matched and $In_yGa_{1-y}As$/GaAs strained layer superlattices grown on Si substrates by *photoreflectance*. These preliminary results show that good quality epilayers from different III-V semiconductors can be grown on Si indicating the possibility of new device materials besides their importance in fundamental research. The experimental data were compared with calculations based on envelope-function approximation and fit to third-derivative functional form of *reflectance* modulation theory.

Reference #359

Characteristics of P-GaAs/n-Si Heterojunctions

by

T. Won, G. Munns, M.S. Unlu, H. Unlu,
J. Chyi, and H. Morkoc

Coordinated Science Laboratory
University of Illinois
1101 W. Springfield Avenue
Urbana, Illinois 61801

Abstract

We have studied the electrical characteristics of P-GaAs/n-Si heterojunction diodes grown by molecular beam epitaxy (MBE) in an effort to investigate the quality of the heterointerface. Both Ga and As prelayers were used to initiate the growth of GaAs epilayers on Si substrates. Current-voltage and capacitance-voltage measurements were made between 300K and 83K. Ideality factors for heterojunction diodes were as good as n = 2.0 despite the 4.1% lattice mismatch between Si and GaAs. At high temperatures the I-V characteristics were dominated by generation-recombination mechanisms which lead to a temperature-independent logarithmic slope with applied bias. By removing a thin layer from the Si surface the surface leakage current was reduced by more than an order of magnitude. The measured intercept voltages, as determined by capacitance-voltage measurements, have no strong dependence on the type of prelayer used to initiate the growth of the GaAs epilayer on Si substrates The maximum spread in measured intercept voltages was about 1 volt, the absolute value of which depends upon the condition of the interface.

Reference #358

Nearly Ideal p/n Junctions Between GaAs and Si (100)

M. S. Unlu, G. Munns, J. Chen, T. Won, H. Unlu and H. Morkoc*
University of Illinois
1101 W. Springfield Avenue
Urbana, Illinois 61801-3082

G. Radhakrishnan and J. Katz
Jet Propulsion Laboratory
Pasadena, California 91109

D. Verret
Texas Instruments
Houston, Texas 77001

ABSTRACT

Electrical characteristics of GaAs(p)/Si(n) interface, both as-grown and annealed at 850°C for 20 minutes in 10% forming gas under As_2 overpressure, were studied by current-voltage (I-V), capacitance-voltage (C-V), and secondary ion mass spectroscopy (SIMS) measurements and compared to those of GaAs(p) epitaxial layers on GaAs(n) substrates. After annealing, ideality factors greater than 2 obtained on Si and GaAs substrates dropped to 1.5 while the apparent built-in voltage, as determined from C-V measurements, enhanced from 2.5 to 1.2V on Si substrates and from 1.1 to 1.2V on GaAs substrates. In addition, the excess current in the forward and reverse bias conditions dropped drastically. No movement of the metallurgical junction was observed within the

*On leave of absence at California Institute of Technology (and the Jet Propulsion Laboratory), Pasadena, CA 91125

Reference #382

GaAs-Si Heterojunction Bipolar Transistor

J. Chen, T. Won, M.S. Unlu, and H. Morkoc
University of Illinois at Urbana-Champaign
1101 West Springfield Avenue, Urbana, Illinois 61801

D. Verret
Texas Instruments, Houston, Texas 77001

Abstract

A GaAs/Si heterojunction bipolar transistor (HBT) structure is proposed having application for high frequency operation. The structure combines the high frequency capability of the GaAs/AlGaAs system with the advanced processing technology of Si. The proposed device consists of n-AlGaAs/p-GaAs emitter and base layers on an n-Si collector with improved junction characteristics at the GaAs/Si heterointerface afforded by thermal annealing. This novel device structure combines the advantages associated with a wide bandgap AlGaAs emitter, the high electron mobility of GaAs, and the substantial reduction in device parasitics accorded the self-aligned structure. Additionally, the proposed device offers the possibility of planar GaAs processing. Using a compact transistor model, calculations of the high speed capability of this transistor are presented. For an emitter-base junction area of 1 μm x 5 μm, optimized f_{max} = 108 GHz and $f_{max} = f_t$ = 89 GHz were computed for the GaAs/Si HBT, compared to 76 GHz and 62 GHz, respectively, for equivalent GaAs/AlGaAs HBTs.

Reference #420

High Speed Performance of $InP/In_{0.53}Ga_{0.47}As/InP$ Double Heterojunction Bipolar Transistors

by

T. Won and H. Morkoc

Coordinated Science Laboratory

University of Illinois

1101 W. Springfield Ave.

Urbana, IL 61801

Abstract

A theoretical comparison of $In_{0.53}Ga_{0.47}As/InP$ and $Al_{0.3}Ga_{0.7}As/GaAs$ heterojunction bipolar transistors has been undertaken in an effort to determine the relative merits of these material system. The analysis uses a compact transistor model and considers devices with self-aligned geometries including both extrinsic and intrinsic parameters. The high electron mobility in the $In_{0.53}Ga_{0.47}As$ base layer and high peak velocity of electrons in the collector depletion layer result in a current gain cutoff frequency in excess of 150 GHz for an $InP/In_{0.53}Ga_{0.47}As$ transistor with base thickness of 0.1 μm. Calculation revealed, however, that maximum oscillation frequency is strongly dependent on the contact resistance of the p-type base layer even for self-aligned base transistor. A maximum oscillation frequency of 138 GHz is theoretically predicted for an $InP/In_{0.53}Ga_{0.47}As$ transistor with base thickness of 0.06 μm, base doping of $1 \times 10^{20} cm^{-3}$, a p-type contact resistance of $1.0 \times 10^{-7}\ \Omega\ cm^2$, a current density of $5 \times 10^4\ A/cm^2$, and a V_{CB} of 5 volt.

Reference #421

An $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As$ Double Heterojunction Bipolar Transistor with Non-alloyed Ohmic Contact Using n^+-InAs Cap Layer

by

T. Won, C.K. Peng, and H. Morkoc

Coordinated Science Laboratory

University of Illinois

1101 W. Springfield Ave.

Urbana, IL 61801

Abstract

We have investigated non-alloyed ohmic contacts on $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As$ double heterojunction bipolar transistors (DHBTs) using an n^+-InAs emitter cap layer grown by molecular beam epitaxy(MBE). Specific contact resistances of 1.8×10^{-7} and 1.3×10^{-6} Ωcm^2 have been measured for the non-alloyed emitter and base contacts, respectively. Non-alloyed contacts have led to I-V characteristics that are more uniform from device to device than those obtained with alloyed contacts. The offset voltage of the common emitter output characterisitics, which arise from the asymmetry of emitter and collector junction turn-on voltages, is less than 50 mV, and the common emitter current gain is around 1,300, maximum being 1,500, at a collector current density of 2.7×10^3 A/cm^2. To our knowledge, these are the highest current gain obtained in this HBT structure prepared by MBE.

Reference #429

Enhanced Ballistic Transport in InGaAs/InAlAs Hot Electron Transistors

J. Chen, U. K. Reddy, D. Mui, C. K. Peng, and H. Morkoç

University of Illinois at Urbana-Champaign

Coordinated Science Laboratory

1101 W. Springfield Avenue

Urbana, IL 61801

Abstract

Hot electron transistors fabricated using a 600 Å InGaAs base and 500 Å InAlAs barrier have shown peak ballistic common base current gain of 0.82 at 77 K despite the large injection energies. Reduction of injection energies by lowering the emitter and collector barriers should lead to even higher ballistic transport ratio due to the reduced Γ−L scattering.

Reference #344

IV. List of Latest Publications

Journal Articles

289. D. Gammon, R. Merlin, D. Huang, and H. Morkoc, "Acceptor Raman Scattering in GaAs/$Al_xGa_{1-x}As$ Quantum Well Structures," *J. Crystal Growth*, Vol. 81, pp. 149-152, Feb (1987).

290. P. W. Yu, G. D. Sanders, D. C. Reynolds, K. K. Bajaj, C. W. Litton, J. Klem, C. K. Peng, and H. Morkoc, "Determination of Trasition Energies and Oscillation Strengths in GaAs–$Al_xGa_{1-x}As$ Multiple Quantum Wells Using Photovoltage Induced Photocurrent Spectroscopy," *Phys. Rev. B*, Vol 35, pp. 9250-9258 (1987).

291. I. Sela, R. Beserman, and H. Morkoc, "Defects Created in Ion-Implanted $Ga_{1-x}Al_xAs$ Alloys," *J. Appl. Phys.* vol. 60, pp. 2316-2319, 1986.

292. K. T. Tsen, J. Klem, and H. Morkoc, "Electronic Raman Scattering from Carbon Acceptors in Undoped GaAs/$Al_xGa_{1-x}As$ Multiple Quantum Wells," *Solid State Commun.*, in print.

293. A. K. M Wennberg, S. N. Ytterboe, C. M. Gould, H. M. Bozler, J. Klem, and H. Morkoc, "Electron Heating in a Multiple-Quantum-Well Structure Below 1K," *Phys. Rev. B*, Rapid Communications, vol. 34, pp. 4409-4411, 1986.

294. K. L. Priddy, D. R. Kitchen, J. A. Grzyb, C. W. Litton, T. Henderson, J. Klem, W. Kopp, and H. Morkoc, "Design of Enhanced Schottky Barrier AlGaAs/GaAs MODFETs using Highly Doped p^+ GaAs Surface Layers," *IEEE Trans. Electron Dev.*, February 1987.

295. H. Morkoc, T. Henderson, W. Kopp, and C. K. Peng, "High Frequency Noise of $In_yGa_{1-y}As/Al_xGa_{1-x}As$ MODFETs and Comparison to GaAs/$Al_xGa_{1-x}As$ MODFETs," *Electron. Lett.*, vol. 22, pp. 578-580, 1986.

296. A. Mysyrowicz, D. Hulin, A. Antonetti, A. Migus, W. T. Masselink, and H. Morkoc, "Dressed Excitons in Multiple Quantum Well Structure: Evidence for an Optical Stark Effect with Femtosecond Response Time," *Phys. Rev. Lett.*, vol. 56, pp. 2748-2751, 1986.

297. D. C. Reynolds, K. K. Bajaj, C. W. Litton, G. Peters, P. W. Yu, R. Fischer, D. Huang, and H. Morkoc, "Lifetimes, Ionization Energies, and Discussion of the Emission Lines in the 1.5040-1.5110-eV Range in GaAs," *J. Appl. Phys.*, vol. 60, pp. 2511-2516, 1986.

298. C. K. Peng, A. Ketterson, H. Morkoc, and P. M. Solomon, "Determination of the Conduction-Band Discontinuity Between $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ Using n^+-InGaAs/InAlAs/n^--InGaAs Capacitors," *J. Appl. Phys.*, vol. 60, pp. 1709-1712, 1986.

299. R. Fischer, W. Kopp, H. Morkoc, M. Pion, A. Specht, G. Burkhart, H. Appelman, D. McGougan, and R. Rice, "Low Threshold Laser Operation at Room Temperature in GaAs/(Al,Ga)As Structures Grown Directly on (100)Si," *Appl. Phys. Lett.*, vol. 48, pp. 1360-1361, 1986.

300. N. Otsuka, C. Choi, L. A. Kolodziejski, R. L. Gunshor, R. Fischer, C. K. Peng, H. Morkoc, Y. Nakamura, and S. Nagakara, "Study of Heteroepitaxial Interfaces by Atomic Resolution Electron Microscopy," Proc. of the PCSI conference January 29, 1986, Pasadena, CA, and *J. Vac. Sci. Technol. B*, vol. 4, pp. 896-899, 1986.

301. B. Valk, T. S. Call, M. M. Salour, W. Kopp, and H. Morkoc, "Optically Pumped Tunable Mode-Locked Si-Doped GaAs Laser," *Appl. Phys. Lett.*, vol. 49, pp. 119-121, 1986.

302. H. Morkoc, "High Speed GaAs Based Devices on Si Substrates," *Proc. Mat. Res. Soc* Spring 1986 (April 15-18, Palo Alto, CA), J. M. Poate and J. C. C. Fan, Editors, (invited)

303. N. Otsuka, C. Choi, Y. Nakamura, S. Nagakura, R. Fischer, C. K. Peng, and H. Morkoc, "Observation of GaAs/Si Epitaxial Interfaces by Atomic Resolution Electron Microscopy," *Proc. Mat. Res. Soc.*, Spring 1986 (April 15-18, Palo Alto, CA), J. M. Poate and J. C. C. Fan, Editors.

304. K. Zanio, R. Bean, R. Kay, R. Fischer, and H. Morkoc, "A HgCdTe/CdTe/GaAs/Si Epitaxial Structure," *Proc. Mat. Res. Soc.*, Spring 1986 pp. 141-146, (April 15-18, Palo Alto, CA), J. M. Poate and J. C. C. Fan, Editors.

305. J. J. Song, Y. S. Yoon, A. Fedotowsky, Y. B. Kim, J. N. Schulman, C. W. Tu, J. M. Brown, D. Huang, and H. Morkoc, "Barrier-Width Dependence of Optical Transitions Involving Unconfined Energy States in GaAs-$Al_xGa_{1-x}As$ Superlattices," *Phys. Rev. B*, Rapid Comm., vol. 34, pp. 8958-8962, 1986.

306. K. T. Tsen and H. Morkoc, "Population Relaxation Time of Nonequilibrium LO Phonons and Electron-Phonon Interactions in GaAs-$Al_xGa_{1-x}As$ Multiple-Quantum-Well Structures," *Phys. Rev. B*, Rapid Communications, vol. 34, pp. 4412-4414, 1986.

307. D. C. Reynolds, K. K. Bajaj, C. W. Litton, P. W. Yu, D. Huang, J. Klem, and H. Morkoc, "Magnetic and Strain Field Splitting of the Emission Lines in the 1.5040-1.5110 eV Range in GaAs," *Appl. Phys. Lett.*, vol. 60, pp. 1767-1769, 1986

308. J. Klem and H. Morkoc, "Molecular Beam Epitaxy Synthesis of Heterostructures," *Proc. of the Metallurgical Society Northeast Regional Meeting on Semiconductor-Based Heterostructures: Interfacial Structural & Stability* May 1-2, 1986, Murray Hill, NJ, (invited), in M. L. Green, Ed., (Worrendale, PA: The Metallurgical Society).

309. N. Otsuka, C. Choi, Y. Nakamura, S. Nagakura, R. Fischer, C. K. Peng, and H. Morkoc, "High Resolution Electron Microscopy of Misfit Dislocations in the GaAs/Si Epitaxial Interface," *Appl. Phys. Lett.*, vol. 49, pp. 277-279, 1986.

310. D. Hulin, A. Mysyrowicz, A. Antonetti, A. Migus, W. T. Masselink, H. Morkoc, H. M. Gibbs, and N. Peyghambarian, "Ultrafast All-Optical Gate with Subpicosecond ON and OFF Response Time," *Appl. Phys. Lett.*, vol. 49, pp. 749-751, 1986.

311. G. B. Norris, D. C. Look, W. Kopp, J. Klem, and H. Morkoc, "Theoretical and Experimental Capacitance-Voltage Behavior of Modulation-Doped $Al_{0.3}Ga_{0.7}As$/GaAs Heterojunctions," Proc. of 6th MBE Workshop August 14-16, 1985 (Univ. of Minn.) and *J. Vac. Sci. Technol. B*, vol. 4, p. 545, 1986.

312. D. A. Neumann, H. Zabel, R. Fischer, and H. Morkoc, "Structural Properties of GaAs on (001) Oriented Si and Ge Substrates," *J. Appl. Phys.*, vol. 61, pp. 1023-1029 (1987).

313. R. Fischer, H. Morkoc, D. A. Neumann, H. Zabel, C. Choi, N. Otsuka, M. Longerbone, and L. P. Erickson, "Material Properties of High-Quality GaAs Epitaxial Layers Grown on Si Substrates," *J. Appl. Phys.*, vol. 60, pp. 1640-1647, 1986.

314. M. I. Aksun, H. Morkoc, L. F. Lester, K. H. G. Duh, P. M. Smith, P. C. Chao, M. Longerbone, and L. P. Erickson, "Performance of Quarter-Micron GaAs Metal-Semiconductor Field-Effect Transistors on Si Substrates," *Appl. Phys. Lett.*, vol. 49, pp. 1654-1655, 1986.

315. T. Henderson, M. I. Aksun, C. K. Peng, Hadis Morkoc, P. C. Chao, Phillip M. Smith, K.-H. G. Duh, and L. F. Lester, "Microwave Performance of a Quarter-Micrometer Gate Low-Noise Pseudomorphic InGaAs/AlGaAs Modulation-Doped Field Effect Transistor," *IEEE Electron Dev. Lett.*, vol. EDL-7, pp. 649-651, 1986.

316. A. Migus, D. Hulin, A. Mysyrowicz, A. Antonetti, W. T. Masselink, H. M. Gibbs, and N. Peyghambarian, "An Ultrafast All Optical Gate With Subpicosecond On and Off Response Time," *Proc. of Inter. Quantum Electronics Conf.*, June 4-13, San Francisco, 1986.

317. V. V. Gridin, R. Beserman, K. P. Jain, and H. Morkoc, "Resonant Raman Scattering from Quasi-Localized Excitons in Semiconductor Quantum Wells," *Superlattices and Microstructures*, in print, 1987.

318. V. V. Gridin, R. Beserman, and H. Morkoc, "Superlattice Electronic Density of States Near the Quantum Well's Top," *Superlattices and Microstructures*, in print, 1987.

319. K. T. Tsen and H. Morkoc, "Picosecond Time-Resolved Raman Studies of the Expansion of Electron-Hole Plasma in GaAs-$Al_xGa_{1-x}As$ Multiple-Quantum-Well structures," *Phys Rev. B*, Rapid Communications, vol. 34, no. 8, pp. 6018-6021, 1986.

320. J. M. Gering, D. A. Crim, D. G. Morgan, P. D. Coleman, W. Kopp, and H. Morkoc, "A Small-Signal Equivalent-Circuit Model for GaAs-$Al_xGa_{1-x}As$ Resonant Tunneling Heterostructures at Microwave Frequencies," *J. Appl. Phys.*, vol. 61, pp. 271-276, 1987.

321. D. Arch, H. Morkoc, P. J. Vold, and M. Longerbone "High-Performance Self-Aligned Gate (Al,Ga)As/GaAs MODFET's on MBE Layers Grown on (100) Silicon Substrates," *IEEE Electron Dev. Lett.*, vol. EDL-7, no. 11, pp. 635-637, 1986.

322. R. Fischer and H. Morkoc, "III-V Semiconductors on Si Substrates," Extended Abstracts of the 18th (1986 International) Conference on Solid State Devices and Materials, talk C-1-1 pp. 105-108 (invited), Tokyo, JAPAN 1986.

323. D. Y. Oberli, D. R. Wake, M. V. Klein, J. Klem, and H. Morkoc, "Transient Raman Scattering in Multiple Quantum Well Structures," *Fifth Topical Meeting on Ultrafast Phenomena*, Snomass, CO, June 16-20, 1986, Springer Verlag, in print.

324. D. Hulin, A. Antonetti, A. Migus, A. Mysyrowitz, H. M. Gibbs, N. Peyghambarian, W. T. Masselink, and H. Morkoc, "Subpicosecond Optical Non-linearities in GaAs Multiple Quantum Well Structures," *Fifth Topical Meeting on Ultrafast Phenomena*, Snomass, CO, June 16-20, 1986, Springer Verlag, in print.

325. S. M. Liu, M. B. Das, C. K. Peng, J. Klem, T. Henderson, W. Kopp, and H. Morkoc, "Pseudomorphic InGaAs/AlGaAs Modulation Doped FET's with Reduced Low Frequency Noise and Thermally Stable Performance," *J. Crystal Growth*, Vol. 81, pp. 359-367 (1987).

326. Vijay K. Arora, David S. L. Mui, and H. Morkoc, "Mobility Degradation in a Quantum-Well Heterostructure of GaAs/AlGaAs Prototype," *Appl. Phys. Lett.*, Vol. 50, pp. 1080-1082 (1987).

327. C. Choi, N. Otsuka, G. Munns, R. Houdré, H. Morkoc, S. L. Zhang, D. Levi, and M. V. Klein, "Effect of In-situ and Ex-situ Annealing on Dislocations in GaAs on Si Substrates," *Appl. Phys. Lett.*, vol. 50, pp. 992-994 (1987).

328. T. Won, G. Munns, R. Houdré, and H. Morkoc, "Interface Charge Polarity of a Polar on Nonpolar Semiconductor: GaAs/Si with Ga and As Prelayers," *Appl. Phys. Lett.*, vol. 49, pp. 1257-1259, 1986.

329. R. Fischer, and H. Morkoc, "III-V Semiconductors on Si Substrates," *Proc. ESSDERC* September 8-11, 1986, Cambridge, England.

330. J. J. Song, Y. S. Yoon, P. S. Jung, A. Fedotowsky, J. N. Schulman, C. W. Tu, D. Huang, and H. Morkoc, "Experimental and Theoretical Studies of Quantized Electronic State Above the Energy Barrier of GaAs/AlGaAs Superlattices," *Proc. of International Conference on Physics of Semiconductors*, August 11-15, 1986.

331. K. K. Bajaj, D. C. Reynolds, C. W. Litton, P. W. Yu, C. K. Peng, and H. Morkoc, "Magneto Optical Studies of GaAs-$Al_xGa_{1-x}As$ Multi Quantum Well Structures," *Proc. of 13th Inter. Symp. on GaAs and Related Compounds*, September 28-October 1, 1986, Las Vegas, Nevada, Institute of Physics Conf. Series 83.

332. K. T. Tsen and H. Morkoc, "The Observation of the Expansion of the Electron-Hole Plasma in GaAs/$Al_xGa_{1-x}As$ Multiquantum Wells," *Proc. of 13th Inter. Symp. on GaAs and Related Compounds*, September 28-October 1, 1986, Las Vegas, Nevada, Institute of Physics Conf. Series 83.

333. D. C. Look, T. Henderson, C. K. Peng, and H. Morkoc, "Mobility and Parasitic Resistance Measurements in AlGaAs/GaAs and AlGaAs/InGaAs MODFET Structures," *Proc. of 13th Inter. Symp. on GaAs and Related Compounds*, September 28-October 1, 1986, Las Vegas, Nevada, Institute of Physics Conf. Series 83, Chapter 8, pp. 557-562.

334. D. C. Reynolds, K. K. Bajaj, C. W. Litton, R. L. Green, P. W. Yu, C. K. Peng, and H. Morkoc, "Magneto Optical Studies of GaAs/$Al_xGa_{1-x}As$ Multi-quantum Well Structures Grown by Molecular Beam Epitaxy," *Phys. Rev. B*, Vol. 35, pp. 4515-4518 (1987)

335. V. K. Arora, D. S. L. Mui, and H. Morkoc, "High-Field Electron Drift Velocity and Temperature in Gallium Phosphide," *J. Appl. Phys.*, vol. 61 (9), pp. 4703-4704 (May 1, 1987).

336. P. J. Restle, M. B. Weissman, G. A. Garfunkel, P. J. Pearah, and H. Morkoc, "1/*f* Noise in GaAs: Evidence for a New Scale Invariance," *Phys. Rev. B*, Rapid Communications, vol. 34, pp. 4419-4422, 1986.

337. M. I. Aksun, H. Morkoc, L. F. Lester, K. H. G. Duh, P. M. Smith, P. C. Chao, M. Longerbone, and L. P. Erickson, "Performance of Quarter Micron GaAs Metal Semiconductor Field Effect Transistors on Si Substrates," *IEDM Tech. Digest*, December 8-10, Los Angeles, Ca, pp. 752-754, 1986.

338. T. Henderson, M. I. Aksun, C. K. Peng, H. Morkoc, P. C. Chao, P. M. Smith, K. H. G. Duh, and L. F. Lester, "Power and Noise Performance of the Pseudomorphic Modulation Doped Field Effect Transistor at 60 GHz," *IEDM Tech. Digest*, December 8-10, Los Angeles, CA pp. 464-466, 1986.

339. V. K. Arora, D. S. L. Mui, and H. Morkoc, "Mobility Degradation and Transferred Electron Effect in Gallium Arsenide and Indium Gallium Arsenide," *IEEE Trans. Electron Dev.*, vol. ED-34, pp. 1231-1238 (1987).

340. D. Gammon, R. Merlin, and H. Morkoc, "Magnetic Field Enhanced Raman Scattering by Confined and Interface Phonons in Semiconductor Superlattices," *Phys. Rev. B Rapid Comm.*, vol. 35, pp. 2552-2555, 1987.

341. U. K. Reddy, G. Ji, T. Henderson, H. Morkoc and J. Schulman, "Investigation of GaAs/(Al,Ga)As Multiple Quantum Wells by Photoreflectance," *J. Appl. Phys.*, vol. 62, pp. 145-151 (July 1, 1987).

342. M. I. Aksun and H. Morkoc, "Characteristic of Shielded Microstrip Lines on GaAs-Si at Millimeter-Wave Frequencies," in *Proc. of Picosecond Electronics and Optoelectronics*, C. H. Lee, F. J. Leonberger, F. Capasso, and H. Morkoc, eds.

343. A. Mysyrowicz, D. Hulin, A. Migus, A. Antonetti, H. M. Gibbs, N. Peyghambarian, and H. Morkoc, "High Speed Phenomena in GaAs Multiple Quantum Wells," in *Proc. of Picosecond Electronics and Optoelectronics*, C. H. Lee, F. J. Leonberger, F. Capasso, and H. Morkoc, eds. (invited.

344. J. Chen, U. K. Reddy, D. Mui, and H. Morkoc "Enhanced Ballistic Transport in InGaAs/InAlAs Hot Electron Transistors," *Appl. Phys. Lett.*, Vol. 51, pp. 1254-1255 (1987).

345. U. K. Reddy, R. Houdrė G. Munns, G. Ji, H. Morkoc, M. Longerbone, L. Davis, B.P. Gu, and N. Otsuka, "Investigation of GaAs/(Al,Ga)As Multiple Quantum Wells Grown on Ge and Si Substrates by Molecular Beam Epitaxy," *J. Appl. Phys.*, Vol. 62, pp. 4858-4862 (1987)

346. P. W. Yu, D. C. Reynolds, K. K. Bajaj, C. W. Litton, D. Huang, and H. Morkoc, "Observation of Monolayer Fluctuations in the Excited States of GaAs/AlGaAs Multiple Quantum Well Structures Using Photocurrent and Reflection Spectroscopics," *Solid State Comm.*, vol. 62, pp. 41-44 (1987).

347. A. J. Nozik, B. R. Thacker, J. A. Turner, J. Klem, and H. Morkoc, "Photocurrent Spectroscopy of Lattice-Matched Superlattice Electrodes in Photoelectrochemical Cells," *Appl. Phys. Lett.*, vol. 50, pp. 34-36, 1987.

348. M. I. Aksun, C. K. Peng, A. A. Ketterson, H. Morkoc, and K. R. Gleason, "High Frequency Modulation Doped Field Effect Transistors in InAlAs/InGaAs/InP Material System," *IEDM Tech. Digest*, Dec. 8-10, Los Angeles, CA pp. 822-825, 1986.

349. M. I. Aksun and H. Morkoc, "GaAs on Si as a Substrate for Microwave and Millimeter-Wave Monolithic Integration," *IEEE Trans. on Microwave Theory and Techniques*, in print.

350. J. Klem, D. Huang, H. Morkoc, Y. E. Ihm, and N. Otsuka, "Molecular Beam Epitaxy Growth and Low Temperature Optical Characterization of $GaAs_{0.5}Sb_{0.5}$ on InP," *Appl. Phys. Lett.*, vol. 50, pp. 1364-1366 (1987).

351. C. K. Peng, M. I. Aksun, A. A. Ketterson, Hadis Morkoc, and K. R. Gleason, "Microwave Performance of InAlAs/InGaAs/InP MODFET's," *IEEE Electron Dev. Lett.*, vol. EDL-8, pp. 24-26, 1987.

352. C. K. Peng, S. Sinha, and H. Morkoc, "Characterization of Graded Interface $In_xGa_{1-x}As/In_{0.52}Al_{0.48}As$ ($0.53 < x < 0.70$) Structures Grown by Molecular Beam Epitaxy," *J. Appl. Phys.*, Vol. 62, pp 2880-2884 (1987).

353. A. Migus, D. Hulin, A. Mysyrowicz, A. Antonetti, W. T. Masselink, H. Morkoc, H. M. Gibbs, and N. Peyghambarian, Post deadline paper Thua conference on Lasers and Electrooptics, June 9-13, (1986).

354. P. L. Gourley, M. Longerbone, S. L. Zhang, and H. Morkoc, "Photoluminescence microscopy of Epitaxial GaAs on Si," *Appl. Phys. Lett.*, Vol. 51, pp. 599-601 (1987).

355. J. J. Song, Y. S. Yoon, P. S. Jung, A. Fedowsky, J. N. Schulman, C. W. Tu, J. M. Brown, D. Huang, and H. Morkoc, "Above Barrier PLE Doublets in $GaAs/Al_xGa_{1-x}As$ Superlattices," *Appl. Phys. Lett.*, Vol. 50, pp. 1269-1271 (1987).

356. P. Roblin, S. C. Kang, A. Ketterson, and H. Morkoc, "Analysis of MODFET Microwave Characteristics," *IEEE Trans. Electron Dev.*, Vol. ED - pp. 1919-1928 (1987).

357. D. C. Reynolds, K. K. Bajaj, P. W. Yu, H. Morkoc, I. Shidlovsky, K. Alavi, anc C. Colvard, "Determination of Interface Microstructure From High Resolution Excitonic Spectra in GaAs/AlGaAs Multi Quantum Wells," *J. Appl. Phys.*, Vol. 62.

358. T. Won, G. Munns, M. S. Unlu, H. Unlu, J. Chyi, and H. Morkoc "Characteristics of P-GaAs/n-Si Heterojunctions Grown by MBE," *J. Appl. Phys.*, Vol. 62, pp. 3860-3865 (1987).

359. U.K. Reddy, G. Ji, D. Huang, G. Munns, and H. Morkoc, "Investigation of $GaAs/Al_xGa_{1-x}As$ and $In_yGa_{1-y}As/GaAs$ Superlattices on Si Substrates," *Appl. Phys. Lett.*, vol. 50 (24), pp. 1748-1750 (June 15, 1987).

360. D. Hulin, A. Migus, A. Antonetti, A. Mysyrowicz, H. M. Gibbs, N. Peyghambarian, H. Morkoc, and W. T. Masselink, "An Untrafast All Optical Gate," *Optical Bistability III*, Ed. H. M. Gibbs, P. Mandel, N. Peyghambarian, and S. D. Smith, Springer-Verlag, New York, p. 42, 1986.

361. D. Hulin, A. Antonetti, A. Migus, A. Mysyrowicz, H. M. Gibbs, N. Peyghambarian, W. T. Masselink, and H. Morkoc, "Subpicosecond Optical Nonlinearities in GaAs Multiple Quantum Wells," Ultrafast Phenomena V, Ed. G. R. Fleming and A. E. Siegman, Springer Series in Chamical Physics, vol. 46, 1986.

362. V. V. Gridin, R. Beserman, Y. L. Khait, and H. Morkoc, "Laser Energy Dependence of the Phonon Frequencies in Thin GaAs/AlAs Superlattices," *Phys. Rev. Lett.*, pending.

363. R. Beserman, V. V. Gridin, V. P. Jain, and H. Morkoc, "Electron Phonon Coupling in GaAlAs," *Phys. Rev. B*, pending.

364. U. K. Reddy, G. Ji, R. Houdré, H. Unlu, D. Huang, and H. Morkoc, " Study of GaAs/AlGaAs and InGaAs/GaAs Multiple Quantum Wells Grown on Non-polar Substrates by Photoreflectance," *Spie Proc. on Modern Optical Characterization Techniques for Semiconductors and Semiconductor Devices*, Bay Point, FL, March 23, 1987, Vol. 794 pp. 116-120, 1987.

365 D. Huang, G. Ji, U. K. Reddy, and H. Morkoc, "Photoreflectance Spectra of $Al_xGa_{1-x}As$," *SPIE Proc. on Growth of Compound Semiconductor Devices*, Bay Point, FL, Vol. 796, pp. 18-21, March 23, 1987.

366. M. J. Junnarhar, K. Shum, S. Chao, R. R. Alfano, and H. Morkoc, "Energy Relaxation and Diffusion of Photoexcited Carriers in Symmetric and Assymetric Quantum Well GaAs/AlGaAs Structures," *SPIE Proc. on Ultrafast Lasers Probe Phenomena in Bulk and Microstructure Semiconductors, Bay Point, FL, March 23, 1987.* (invited), Vol 793, pp. 6-18, 1987.

367. D. Oberli, D. Wake, M. V. Klein, T. Henderson, and H. Morkoc, "Time Resolved Raman Scattering in GaAs Quantum Wells," *SPIE Proc. on Ultrafast Lasers Probe Phenomena in Bulk and Microstructure Semiconductors, Bay Point, FL, March 23, 1987*, (invited), Vol. 793, pp. 58-62, 1987.

368. J. Klem, D. Huang, H. Morkoc, and N. Otsuka, "Growth and Characterization of $GaAs_{1-x}Sb_x$ on InP by Molecular Beam Epitaxy," *SPIE Proc. on Growth of Compound Semiconductor Devices*, Bay Point, FL, March 23, 1987, Vol. 796, pp. 18-21, 1987.

369. R. Houdré, G. Munns, H. Morkoc, C. Choi, N. Otsuka, S. L. Zhang, D. Levi, and M. V. Klein, "Dislocation Reduction via Annealing of GaAs Grown on Si Substrates," *SPIE Proc. on Growth of Compound Semiconductor Devices, Bay Point, FL*, March 23, 1987, Vol. 796, pp.27-31, 1987.

370. C. K. Peng and H. Morkoc, "MBE Growth and Characterization of Lattice Matched and Strained Channel $In_xGa_{1-x}As/In_yAl_{1-x}As$ Modulation Doped Structures on InP," *SPIE Proc. on Growth of Compound Semiconductor Devices, Bay Point, FL*, March 23, 1987, Vol. 796, pp. 44-48, 1987.

371. H. Unlu and H. Morkoc, "Modulation Doped FETs and Other High Speed III-V transistors," *SPIE Proc. on Characterization of Very High Speed Semiconductor Devices and Integrated Circuits, Bay Point, FL, March 23, 1987*, (invited) Vol. 792, pp. 12-28, 1987.

372. D. Hurley, S. Tamaro, J. P. Wolfe and H. Morkoc "Imaging of Acoustic Phonon Stopbands in Superlattices," *Phy. Rev. Lett.*, Vol. 58 pp. 2446-2449 (1987).

373. C. Whiteside, G. Bosman, and H. Morkoc "Velocity Fluctuation noise in AlGaAs/GaAs Interfaces" *Proc. of Inst. Conf. on Noise and 1/f Noise*, Montreal, 1987.

374. G. Ji, D. Huang, U. K. Reddy, H. Unlu, and H. Morkoc "Determination of Band Offsets in AlGaAs/GaAs and InGaAs/GaAs Multiple Quantum Wells," *J. Vac. Sci., and Technol.*, B 5(5), pp. 1346-1352, 1987.

375. G. Ji, D. Huang, U.K. Reddy, T. Henderson, R. Houdré and H. Morkoc "Optical Investigation of Highly Strained InGaAs/GaAs Multiple Quantum Wells," *J. Appl. Physics*, Vol. 62, pp. 3366-3373 (1987).

376. C. Whiteside, G. Bosman, and H. Morkoc "Velocity Fluctuation, Noise Measurements in AlGaAs/GaAs Interfaces," *IEEE Trans. on Electron Dev.*, Vol. ED 34, pp. 2530-2534, (1987)

377. T. Won, R. Munns, R. Houdré and H. Morkoc "Comments on Interface Charge Polarity of A Polar on Nonpolar Semiconductor: GaAs/Si with Ga and As Prelayers," *Appl. Phys. Lett.*, Vol. 51, p. 1756 (1987)

378. H. Morkoc, J. Chen, T. Henderson, U. K. Reddy, and S. Luryi, "Response to Comments on Observation of A Negative Differential Resistance Due to Tunneling through A Single Barrier into A Quantum Well," *Appl. Phys. Lett.*, vol. 50 (22), pp. 1610-1611 (June 1, 1987).

379. N. Chand, T. Henderson, J. Klem, W. T. Masselink, R. Fischer, Y. C. Chang, and H. Morkoc "Reply to Comment on Comprehensive Analysis of Si-Doped $Al_xGa_{1-x}As$ ($x=0$ to 1): Theory and Experiments," *Phys Rev. B*, Vol. 36, pp. 4454-4455 (1987)

380. G. Munns, R. Houdré and H. Morkoc "Molecular Beam Epitaxial Growth of GaAs on Si," *SAMPE Electronics Materials and Processes Conference*, Santa Clara, California, June 23-25, 1987 (Invited).

381. H. Z. Chen, H. Wang, A. Ghaffari, H. Morkoc and A. Yariv, " Measurementof Au/GaAs/$Al_xGa_{1-x}As$ Hetero-Schottky Barrier Height and GaAs/$Al_xGa_{1-x}As$ Conduction-Band Discontinuity," *Appl. Phys. Lett.*, Vol. 51, pp. 990-991, (1987).

382. M. S. Unlu, G. Munns, J. Chen, T. Won, H. Unlu, H. Morkoc G. Radhakrishnan, J. Katz, and D. Verret, "Characterizations of Annealed p/n Junctions between GaAs and Si (100)," *Appl. Phys. Lett.*, Vol. 51, pp. 1995-1997 (1987).

383. T. Won and H. Morkoc "High Speed Performance of InP/InGaAs/InP Double Heterojunctions Bipolar Transistors," *Proc. of IEEE Bipolar Circuits and Technology Conf.*, September 21-22, 1987, Minneapolis.

384. U. K. Reddy, G. Ji, T Henderson, D. Huang, R. Houdré H. Morkoc and C. W. Litton,"Interband Transitions in InGaAs/GaAs Strained Layer Superlattices," *Phys. Rev. B*, in print.

385. H. Zabel, N. Lucas, R. Feidenhans'l, J. Als-Nielsen, and H. Morkoc "Structure of Heteroepitaxial GaAs on Si," *Proc. of Superlattices, Microstructures and Devices*, August 17-20, 1987, Chicago.

386. D. Gammon, L. Shi, R. Merlin, G. Ambrazevicius, K. Ploog, and H. Morkoc "Enhanced and Quenched Raman Scattering by Interface Phonons in Semiconductor Superlattices: What are the Effects?" *Proc. of Superlattices, Microstructures and Devices*, August 17-20, 1987, Chicago.

387. G. Ji, D. Huang, U. K. Reddy, T. S. Henderson, and H. Morkoc "Optical Investigations of Highly Strained InGaAs/GaAs Multiple Quantum Wells," *Proc. of Superlattices, Microstructures, and Devices*, August 17-20, 1987, Chicago.

388. P. P. Szydeik, S. A. Alterovitz, E. J. Haugland, B. Segall, J. Klem, and H. Morkoc "Shubnikov-DeHaas Measurements of the 2D-Electrn Gas in Pseudomorphic InGaAs ($x \leqslant 0.2$) Grown on GaAs, " *Proc. of Superlattices, Microstructures, and Devices*, August 17-20, 1987.

389. K. Shum, M. R. Junnarkar, H. S. Chao, R. R. Alfan, and H. Morkoc "Non-equilibrium Carrier Phonon Effect on the Time Dependent Relaxation of Hot Carriers in GaAs Quantum Wells," *Proc. of Superlattices, Microstructures, and Devices*, August 17-20, 1987, Chicago.

390. K. Shum, M. R. Junnarkar, H. S. Chao, R. R. Alfano, and H. Morkoc "Direct Measurement of Ultrafast Electron-hole Plasma Expansion at High Density in An Assymmetric GaAs Quantum Well," *Proc. of Superlattices, Microstructures, and Devices*, August 17-20, 1987, Chicago.

391. J. J. Song, P. S. Jung, Y. S . Yoon, A. Fedokowsky, Y. B. Kim, J. N. Schulman, C. W. Tu, and H. Morkoc "Optical Studies of Unconfined Transitions in GaAs/AlGaAs Superlattices," *Proc. of Superlattices, Microstructures, and Devices*, August 17-20, 1987, Chicago.

392. H. Z. Chen, A. Ghaffari, H. Wang, H. Morkoc and A. Yariv, "Low Threshold (~ 600 A/cm^2 at Room Temperature) GaAs/AlGaAs Lasers on Si (100), " *Appl. Phys. Lett.*, Vol. 51, pp. 1320-1321 (1987).

393. H. Z. Chen, A. Ghaffari, H. Wang, H. Morkoc and A. Yariv, "Continuous Wave Operation of Extremely Low Threshold GaAs/AlGaAs Broad Area Injection Laser on Si (100) Substrate at Room Temperature," *Optics Letters*, Vol. 12, pp. 812-813 (1987).

394. D. Huang, G. Ji, U. K. Reddy, H. Morkoc, F. Xiong, and T. Tombrello, "Photoreflectance, Absorption, and Nuclear Resonance Reaction Studies of $Al_xGa_{1-x}As$ Grown by Molecular Beam Epitaxy," *J. Appl. Phys.*, in print.

395. D. Oberli, D. R. Wake, M. Klein, J. Klein, T. Henderson, and H. Morkoc "Time Resolved Raman Scattering in GaAs Quantum Wells," *Phys. Review Lett.*, Vol. 59, pp. 696-698 (1987).

396. D. Levi, S. L. Zhang, M. V. Klein, J. Klem, and H. Morkoc "Raman Study of the Effects of Annealing on Folded LA and Confined LO Phonons in GaAs-AlAs Superlattices," *Phys. Review B*, Vol. 36, pp. 8032-8037 (1987).

S. L. Zhang, D. Levi, T. A. Grant, M. V. Klein, J. Klem, and H. Morkoc "Investigation of Confined Optic Phonons and Their Annealing Effects in GaAs/AlAs Superlattices," *Proc. of 10th Int. Conf. on Raman Spect.*, Chemical Physics Institute, University of Oregon, 1986.

. A. Schenstrom, M. Levy, B. K. Sharma, and H. Morkoc "Frequency Dependent Breakdown of the Dissipation Less State in the Quantum Hall Effect," *Phy. Rev. Lett.*, pending.

. K. Shum, M. R. Junnarkar, H. S. Chao, R. R. Alfano, and H. Morkoc "Observation of Ultrafast Lateral Diffusion of Photogenerated Carriers in An Assymetric GaAs Quantum Well," *Phy. Rev. Lett.*, pending.

. K. Shum, M. R. Junnarkar, H. S. Chao, R. R. Alfano, and H. Morkoc "Non-equilibrium Phonon Effect on the Energy Relaxation and Lifetime of Photogenerated Carriers in Undoped GaAs Quantum Wells," *Phys. Rev. B.*, pending.

. D. Y. Oberli, D. R. Wake, M. V. Klein, T. Henderson, and H. Morkoc "Picosecond Raman and Luminescence Studies of Carrier Relaxation in Quantum Wells," *Proc. of 3rd USA-USSR Symposium on Laser Optics of Condensed Matter*, Leningrad, June 1-6, 1987.

2. M. V. Klein, T. A. Gant, D. Levi, S. L. Zhang, T. Henderson, J. Klem, and H. Morkoc "Raman Studies of Phonons in GaAs/AlGaAs Superlattices," *Proc. of 3rd USA/USSR Symposium on User Optics of Condensed Matter*, Leningrad, June 1-6, 1987.

3. D. A. Neumann, H. Zabel, and H. Morkoc "Terracing in Strained Layer Superlattices," *J. Appl. Phys.*, in print.

4. Y. E. Ihm, N. Otsuka, J. Klem, and H. Morkoc "Ordering in $GaAs_{1-x}Sb_x$ Grown by Molecular Beam Epitaxy," *Appl. Phys. Lett.*, Vol. 51, pp. 2013-2015 (1987).

5. D. Huang, Y. C. Chang, R. Houdré and H. Morkoc "Excitonic Absorption in Modulation Doped GaAs/AlGaAs Quantum Wells, *Phys. Rev. B*, in print.

6. H. Z. Chen, A. Ghaffari, H. Morkoc and A. Yariv, "Very Low Threshold (under 100 A/cm^2 GaAs/AlGaAs Graded Index Separate Confinement Lasers Grown by Molecular Beam Epitaxy," *Electronics Letts.*, Vol. 23, pp. 1334-1335 (1987).

7. H. Z. Chen, A. Ghaffari, H. Morkoc and A. Yariv, " Effect of Substrate Tilting on Molecular Beam Epitaxial Grown AlGaAs/GaAs Lasers Having Very Low Threshold Current Densities," *Appl. Phys. Letts.*, Vol. 51, pp. 2094-2096 (1987).

8. R. Vincent, D. Cherns, S. J. Bailey, and H. Morkoc " Structure of AlGaAs/GaAs Multilayers Imaged in Superlattice Reflections," *Phil. Mag. Lett.*, Jan 1987

9. D. C. Reynolds, K. K. Bajaj, C. Leak, G. Peters, W. Theis, P. W. Yu and H. Morkoc " Observation of Discrete Transitions Associated with Hydrogenic Donors Located at Different Lattice Positions in GaAs-AlGaAs Multi-Quantum Well Structures Usinc Excitation Spectroscopy," *Phys. Rev. Lett.*, pending.

410. D. C. Reynolds, K. K. Bajaj, G. Peters, C. Leak, W. M. Theis, P. W. Yu and H. Morkoc "Correlation Between the Light and Heavy Hole Free Excitron Fine Structure in $Al_xGa_{1-x}As/GaAs$ Multi-Quantum Well Using Photolumicescence Excitation Spectroscopy," *Phys. Rev. B. Rapid Comm.*, pending.

411. W. M. Theis, G. D. Sanders, C. E. Leak, K. K. Bajaj and H. Morkoc "Excitonic Transistors in GaAs, GaAlAs Quantum Wells Observed by Photoreflectance Spectroscopy: Comparison with a First Principle," *Phys. Rev. B*, pending.

412. P. L. Derry, H. Z. Chen, H. Morkoc, A. Yariv, K. Y. Lau, N. Bar-Chaim, K Leonard, J. Rosenberg, "Ultra Low Threshold Graded Index Separate Confinement Heterostructure Single Quantum Well (Al,Ga)As Lasers," Presented at the 8th MBE Workshop Sept. 9-11, 1987, UCLA, to be published in *JVSTB*.

413. F. Xiong, T. A. Tombrello, H. Z. Chen, H. Morkoc and A. Yariv, "Direct Determination of Al Depth Fluctuation in MBE Grown $Al_xGa_{1-x}As$," Presented at the 8th MBE Workshop Sept. 9-11, 1987, UCLA, to be published in *JVSTB*.

414. Y. E. Ihm, N. Otsuka, J. Kleim and H. Morkoc "Ordering in $GaAs_xSb_{1-x}As$ Grown by Molecular Beam Epitaxy," Presented at the 8th MBE Workshop Sept. 9-11, 1987, UCLA, to be published in *JVSTB*.

415. K. T. Tsen and H. Morkoc " Picosecond Raman Studies of the Spatial Phonons in the $Al_xGa_{1-x}As$ Layers of GaAs/AlGaAs Multiple Quantum Well Structures," *Phys. Rev. B Rapid Comm.*, pending.

416. T. Henderson, U. K. Reddy, G. Ji, H. Morkoc and N. Otsuka, "Characterization of Pseudomorphic InGaAs/AlGaAs MODFET Structures Grown by Molecular Beam Epitaxy," *Tech. Digest of 1987 Int. Elect. Dev. Meeting*, Dec. 7-9, 1987, Washington, D.C., pp. 418-421.

417. J. Chen, M. S. Unlu, T. Won, G. Munns, H. Morkoc and A. Yariv, "Electrical Properties of Thermally Annealed p-GaAs/Sn-Si Heterojunctions and the Implications for GaAs/Si Heterojunction Bipolar Transistors, *Tech. Digest of 1987 Int. Elec. Dev. Meeting*, Dec. 7-9, 1987, Washington, D.C., pp. 82-85.

418. H. Z. Chen, J. Paslaski, A. Ghaffari, H. Wang, H. Morkoc and A. Yariv, "High Speed Modulation and CW Operation of AlGaAs/GaAs Lasers on Si," *Tech. Digest of 1987 Int. Elect. Dev. Meeting*, Dec. 7-9 ,1987, Washington, D.C., pp. 238-241.

419. Y. E. Ihm, N. Otsuka, J. Klein and H. Morkoc "Ordering in $GaAs_{1-x}Sb_x$ Grown by Molecular Beam Epitaxy," *Proc. of MRS Fall Meeting (Epitaxy of Semiconductor Layered Structures)*, Eds. R. T. Tung, L. R. Dawson and R. L. Gunshor.

420. J. Chen, T. Won, M. S. Unlu, H. Morkoc and D. Verret, "GaAs/Si Heterojunction Bipolar Transistors," *Appl. Phys. Lett.*, in print.

421. T. Won and H. Morkoc "High Speed Performance of InP/InGaAs/InP Double Heterojunction Bipolar Transistors," *Appl. Phys. Lett.*, in print.

422. H. Z. Chen, J. Paslaski, A. Yariv and H. Morkoc "High Frequency Modulation of AlGaAs/GaAs Lasers Grown on Si by Molecular Beam Epitaxy," *Appl. Phys. Lett.*, in print.

423. D. Huang, J. Chyi, J. Klem and H. Morkoc "Photoluminescence Study of Molecular Bean Epitaxial Grown $GaAs_{1-x}Sb_x$ ($0 \leqslant x \leqslant 0.5$) on GaAs and InP Substrates," *J. Appl. Phys.*, in print.

424. C. K. Peng, J. Chyi, J. Chen, and H. Morkoc "Extremely Low Non- alloyed and Alloyed Contact Resistances Using InAs Cap Layers on $In_{0.53}Ga_{0.47}As$ by Molecular Beam Epitaxy," Appl. Phys. Lett., pending.

425. T. Henderson and H. Morkoc "Performance of AlGaAs/InGaAs Pseudomorphic MODFETs at Cryogenic Temperatures," *Proc. of Electron. Chem. Soc.*, *Low Temperature Electronics*, Oct. 19-24, 1987, Hawaii (Invited).

426. H. Z. Chen, H. Morkoc and A. Yariv, "Very Low Threshold AlGaAs/GaAs Lasers Grown on Tilted (100) Substrates by Molecular Beam Epitaxy," *Tech. Digest of 1987 IEDM*, Dec 7-9, 1987, pp. 887-888.

427. A. S. Bommannavar, A Wobenschuss, G. E. Ice, C. J. Sporks, H. Morkoc and H. Zabel, "X-ray diffraction study of a Thin GaAs Film on Si (100)," *Proc. of Materials Asn. Soc.*, Fall meeting, 1987.

428. J. Paslaski, H. Z. Chen, H. Morkoc and A. Yariv, "High Speed GaAs p/n Diodes Grown on Si Substrates by Molecular Beam Epitaxy," *Appl. Phys. Lett.*, pending.

429. C. K. Peng, T. Won and H. Morkoc "$In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As$ Double Heterojunction Bipolar Transistor with Non-alloyed Ohmic Control Using n^+ InAs Cap Layer," *IEEE Electron. Device Lett.*, pending.

430. W. Dobbelaere, S. Kalem, D. Huang, S. Unlu and H. Morkoc " InGaAs/GaAs Strained Layer Multiple Quantum Well Electro-absorption Optical Modulation," *Electronics Lett.*, pending.

431. G. Ji, W. Dobbelaere, D. Huang and H. Morkoc "Optical Transitions Involving Unconfined Energy States in InGaAs/GaAs Multiple Quantum Wells," *Phys. Review B.*, pending.

432. P.W. Yu, G.D. Sanders, D.C. Reynolds, K.K. Bajaj, C.W. Litton, J. Kleim, D. Huang, H. Morkoc "Determination of Transiton Energies and Oscillator Strengths in $GaAs/al_xGa_{1-x}As$ Multiple Quantum Wells Using Photovoltage - Induced Photocurrent Spectroscopy," *Phys. Review B.*, Vol. 35, pp. 9250-9258 (1987).

433 I. Sela, V.V. Gridin, R. Beserman, R. Sarfaty, D. Feketa, and H. Morkoc "Distribution of Atoms in Mixed III-V Compounds," *J. Appl. Phys.*, in print.